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Technical Performance Report
to
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and the
Office of Naval Research
on

Millimeter-Wave Characterization of GaAs Devices and IC's

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Millimeter-Wave Characterization of GaAs Devices and IC's

I. Overview

Continuing advances in millimeter-wave analog and picosecond-delay digital integrated circuits have been made for several years, yet the majority of measurements reported have been extrapolated from DC-40 GHz data, giving only a linear projection to predict the EHF performance of these devices and circuits. The only solution to this problem is to develop measuring instruments with greater bandwidths. To date, we have produced successful results in developing an on-wafer GaAs through-line probe to extend the bandwidths and capabilities of an all-electrical network analyzer.

II. Introduction

Coplanar waveguide transmission line (CPW) passive probes have become very popular for on-wafer characterization of integrated circuits. Since this transmission line has all conductors on one side of the substrate, it is a low parasitic medium for transmission from the input connector to the device under test. The entire line can be formed with one mask step and does not require backside metalization or via holes. Since the CPW formed on a semi-insulating substrate (e.g. GaAs) has a characteristic impedance which only depends on the center conductor width-to-ground gap, the impedance can easily be changed. We have improved upon our ultra-short pulse generating capabilities with highly optimized non-linear transmission lines (NLTL) incorporated into the design of very wide-bandwidth electrical samplers and also into an integrated circuit directional bridge. Since these integrated circuits are small, they can be mounted directly on an IC probe tip. This capability, by bringing the measurement instrument into contact with the circuit to be tested almost completely solves the interconnect losses. By placing the MMICs in an alumina tip package, we are able to measure s-parameters up to 85 GHz. Above 100 GHz, the parasitics of the connection between the MMIC samplers and the alumina probe tip become intolerable and the alumina tip must be eliminated. Since the GaAs IC cannot be flexed, we have developed a parallelogram flexure probe which will allow a controlled normal force to be applied to the tip. As a first goal, we decided to develop a through-line GaAs probe which will allow repeatable measurement at microwave frequencies. This passive GaAs probe has been the subject of intensive development over the past year, with promising results obtained thus far.

III. Results Achieved

A. Probe / Probe Station Design

The probe / probe station were developed to meet the following criteria:

1) Integrate the high bandwidth circuit elements onto a compact substrate (MMIC hybrid) that can be brought into direct contact with the device under test.
2) Isolate the MMIC hybrid from the probe arm, manipulator and coaxial cable forces by a conductor flexure meeting contact force requirements and good to 50 GHz.
3) Repeatably control the contact forces so as to maintain physical integrity of device under test and the probe tip itself.
4) Limit conductors to the CPW configuration with minimum feasible length.
5) Adopt existing 3-axis manipulator to control the location of the probe within one micron in X, Y and Z direction.
6) Allow tilt control in order to set the coplanarity of the probe tip with the device under test.

The probe station must have a firm base so that probe tip coplanarity will not change with repeated contacts, changing cables, changing direction and vibration. We decided to use Newport micropositioners on a work table. Differential micrometers with .5 inch travel and .5 um resolution allow testing of structures with varying dimensions on the wafer. The probe is connected to the XYZ stage using a tilt control and XYZ adaptor, and has a main body consisting of four 50 GHz connectors plus 2 ten-pin DC connectors. RF connectors are placed at the sides of the main body in order to allow good access with a wrench, allowing the DC connector to be placed on top of the main body. The GaAs tip is placed on a replaceable tip package, connected to a transition package attached to the main body by two 2 mil BeCu parallelogram flexure units. RF connectors are connected to the transition package using 22 mil semi-rigid coax cables, and 12 magnet wires are used to connect the DC connector to the transition package. The GaAs probe / GaAs probe station assembly is shown in Figs. 1 and 2.

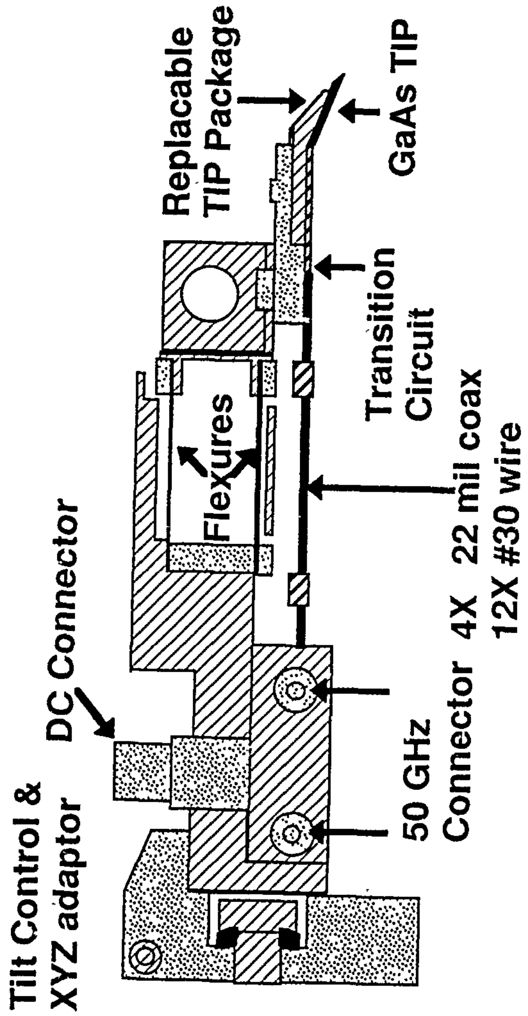

Fig. 1a Diagram of active probe with GaAs tip

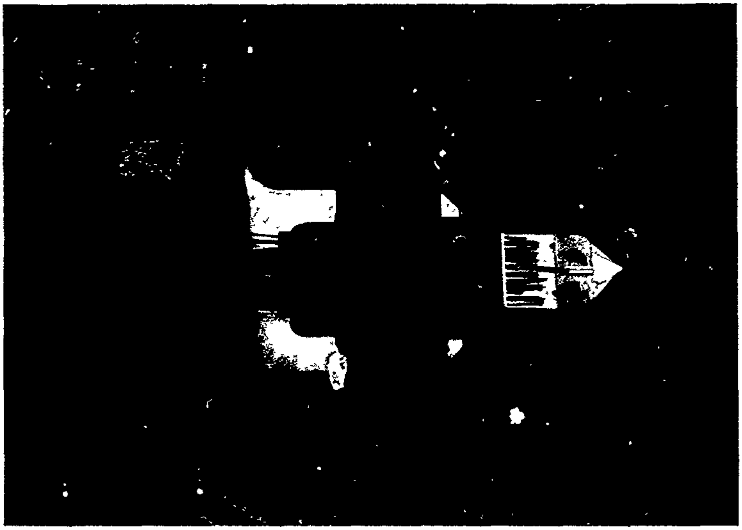

Fig. 1b Photograph of GaAs probe (1.25X) overall bottom view

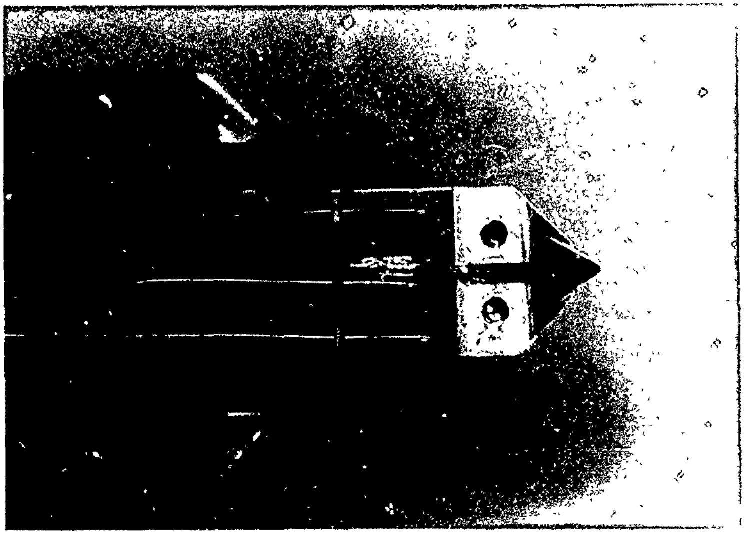

Fig. 1c Photograph of GaAs probe (2.7X) tip package transition to 22 mil coax

Fig. 1d Photograph of GaAs probe (2.45X) top view of tip package

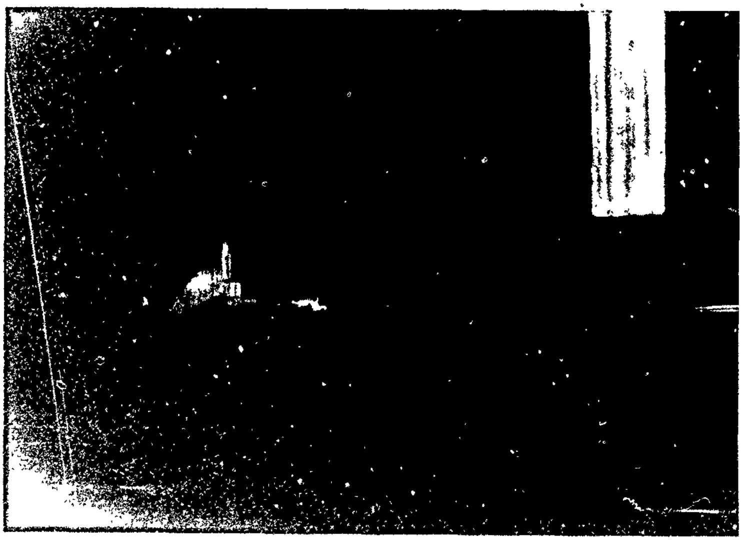

Fig. 1e Photograph of GaAs probe (2.9X) side view of tip package

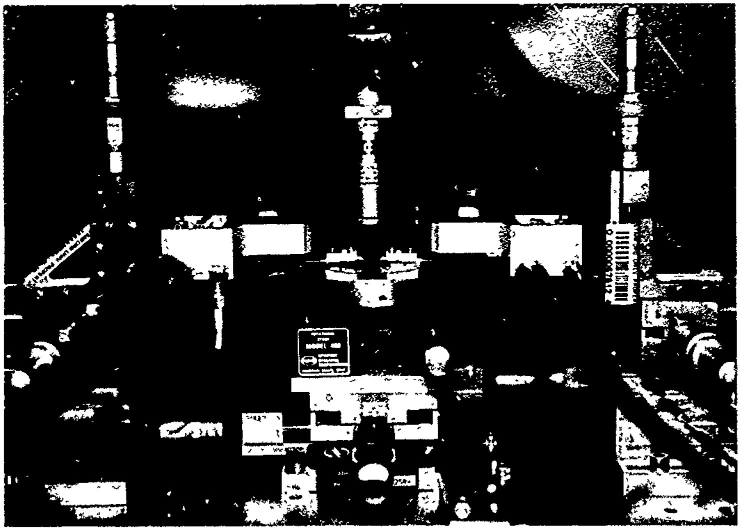

Fig. 2a Photograph of GaAs probe station (.43X) overall view

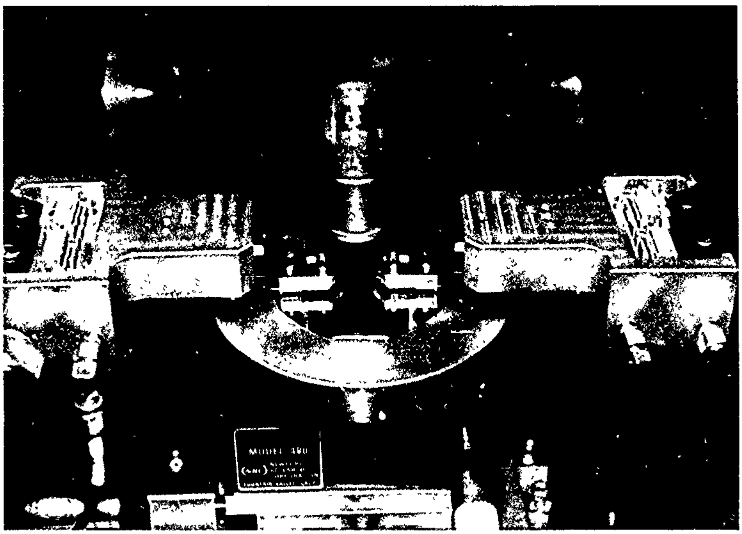

Fig. 2b Photograph of GaAs probe station (.75X) overall view

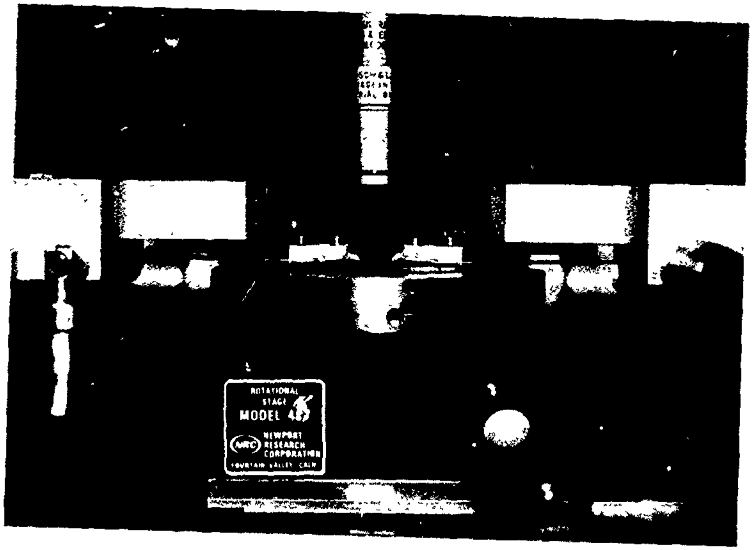

Fig. 2c Photograph of GaAs probe station (.78X) side view

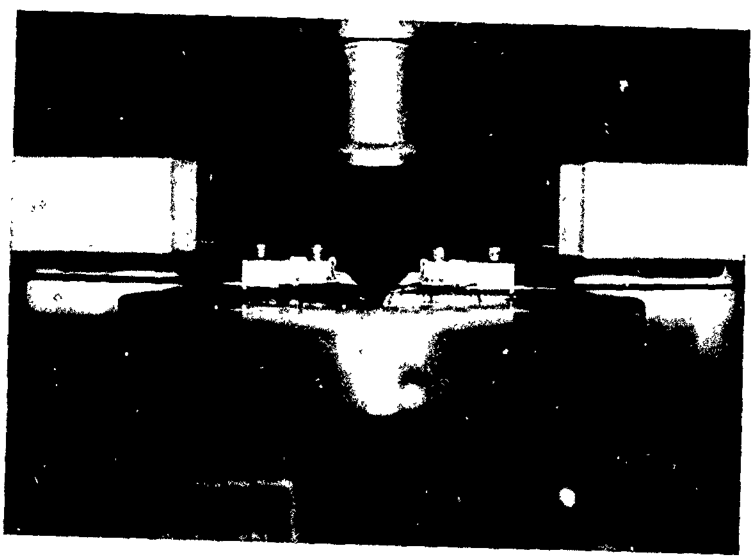

Fig. 2d Photograph of GaAs probe station (1.2X) side view

The probe flexure has a characteristic response of 10 grams/mm, as shown in Fig. 3. In order to make a good microwave contact we only need 2 grams of force. The tip has passed 100 um of scribing in the X and Y directions with 10 gram force applied without degradation of the tip quality. The GaAs probe / probe station mechanical performance is summarized in Table 1.

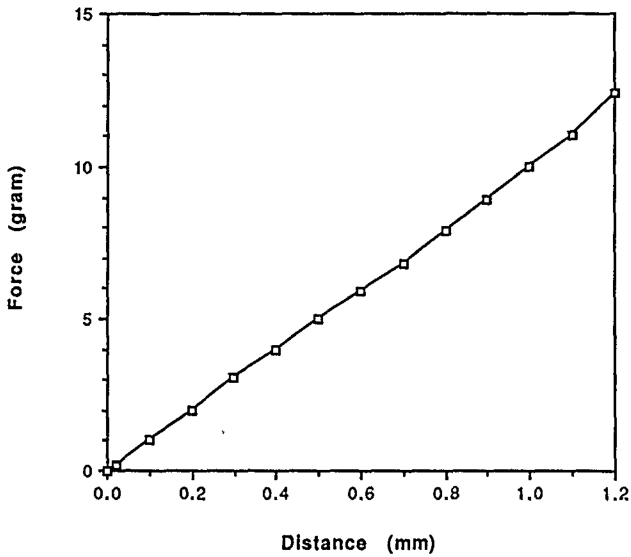

Fig. 3 Probe flexure characteristic response

Table 1
Summary of Mechanical Specifications

Number of signal lines	4 RF and 12 DC
Signal line frequency	50 GHz
Signal line impedance	50 ohm
Signal line cross talk	-50 dB
Probe footprint	variable
Position accuracy	1 um
Rigidity	enough to maintain coplanarity
Repeatability	1 um
Probe positioning range	.5 in
Probe positioning resolution	.5 um
Wafer positioning range	.5 in
Length	10 cm
Width	7 cm

B. Transmission Line Circuit

Since the final design goal was to obtain 300 GHz measurement capability, the dimensions of the CPW at the probe tip were selected to make good contact at millimeter wavelengths. A 50 ohm CPW transmission line on a 500 micron thick GaAs has the following properties:

S = Signal conductor width = 1.5 W
W = Signal-to-Ground spacing
Wg = Ground conductor width > S+2W
t = conductor thickness = 1.6 um (Stanford process)
λ_d = 378 um @ 300 GHz
Skin depth = 2.44 um / SQRT[f(GHz)] = 1410 A @ 300 GHz

Radiation can be minimized by making S+2W less than $\lambda_d/20$. Conductor losses can be reduced by increasing S. Table 2 summarizes the losses for a 500 micron long CPW transmission line.

Table 2
500 um Long CPW Transmission Line

CPW (S/W) um	Conductor loss dB	Radiation loss dB	Dielectric loss dB
90/60	-.15	-5.6	-.033
20/13	-.57	-.27	-.033
10/7	-1.36	-.073	-.033
6/4	-2.2	-.025	-.033

As a compromise between conductor and radiation losses, a CPW transmission line with 20-13 dimension at the probe tip was used.

C. Probe contact material

The choice of probe contact material is very important to the operation of the probe. These contacts must have low DC and microwave contact resistance, be capable of fabrication in small sizes, and have reasonable wear resistance. Among choices such as gold balls, silver epoxy, plated nickel and solder ball, plated nickel is the best. Between the two methods available for nickel plating (electric plating and electroless plating) electric plating on Au directly was used for best adhesion.

Photoresist was applied on both sides of the wafer to avoid backside plating, then the wafer was placed in 500 ml of hot nickel solution ($NiSO_4\ 6H_2O$: 165 gram, H_3BO_3 : 15 gram, DI H_2O) for 2 minutes (Fig. 4).

D. GaAs etching

The purpose of etching is to allow the user to see the exact location of the tip with the contact to device under test. To achieve this goal it is necessary to etch 500 um of GaAs in [100] direction, normal to the surface. Also the edge angle should be less than 90 degrees in order that the probe tip be visible. H_2SO_4 -H_2O_2 -H_2O which has an etch rate of 10 um/min was selected for this purpose. The best method is to etch the wafer 200-300 μm and then remove the back side photoresist and allow the etch solution to attack from both sides. Since the etch rate is dependent on the etch solution temperature, we developed a special wafer holder which keeps a wafer horizontally and permits good etchant flow (Fig. 5). The GaAs tip is shown in Fig. 6.

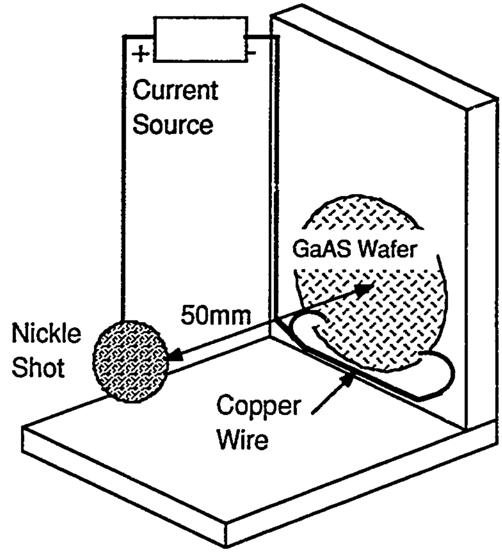

Fig. 4 Nickel plating setup

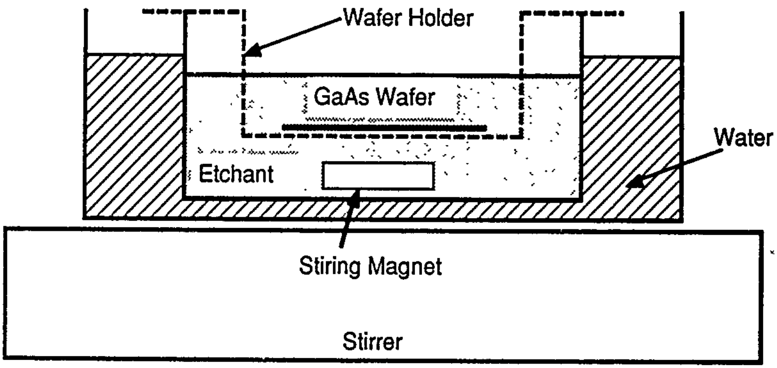

Fig. 5 GaAs etching setup

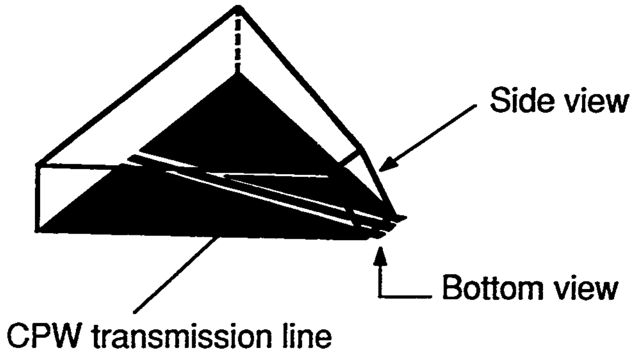

Fig 6a. Diagram of micromachined GaAs tip

Fig. 6b Photograph of GaAs tip side view (110X)

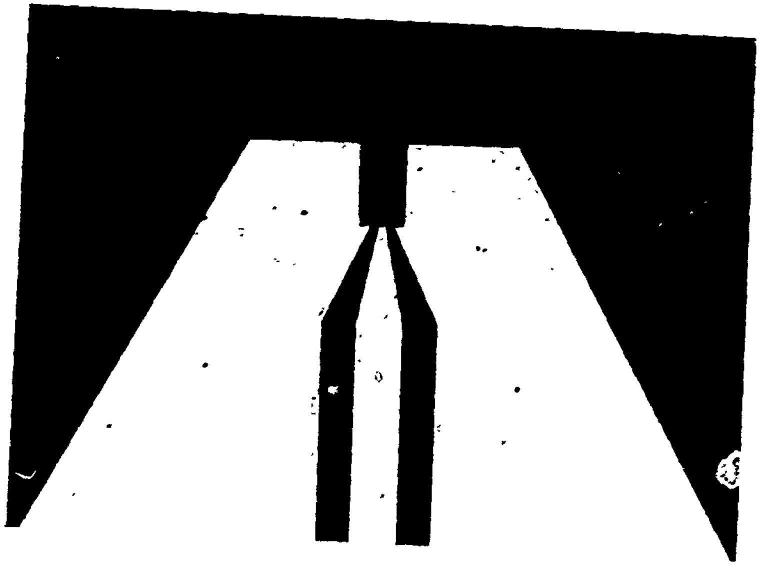

Fig. 6c Photograph of GaAs tip bottom view (110X)

E. Probe Tip Fabrication Process

The GaAs tip processing steps are:

1. Wafer Cleaning.
2. Sputter 1000 A SiO_2.

   In order to improve Au to GaAs adhesion a thin layer of titanium is required. But the GaAs etch solution attacks Ti. Therefore, SiO_2 buffer layer is needed in order to protect the Ti layer during GaAs etching process.
3. Evaporate 1.6 um of Au.
4. Plate 4 um of nickel ($NiSO_4\ 6H_2O$: H_3BO_3 : H_2O).
5. Evaporate 500 A Au and lift-off.
6. Etch GaAs (H_2SO_4 : H_2O_2 : H_2O).
7. GaAs Saw.

   A MicroAutomation 1006A saw was purchased and a procedure for cutting the GaAs into tips has been developed. A schematic of through-line tip mask is shown in Fig. 7 and a close up view of the nickle and the SiO2 masks are shown in Fig. 8. The processing steps are illustrated in Fig. 9.

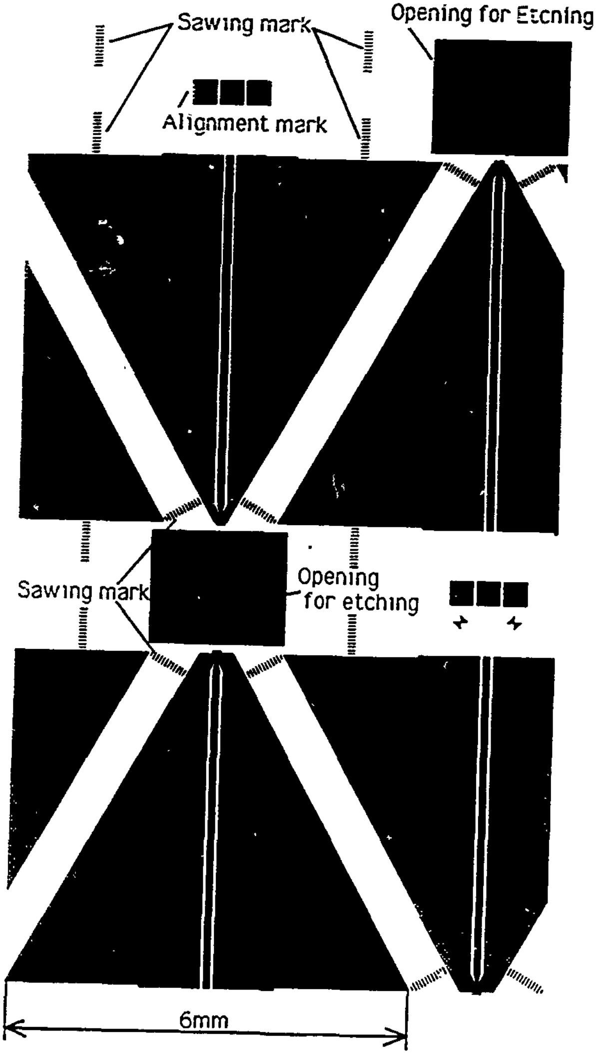

Fig. 7 Schematic of through-line tip mask

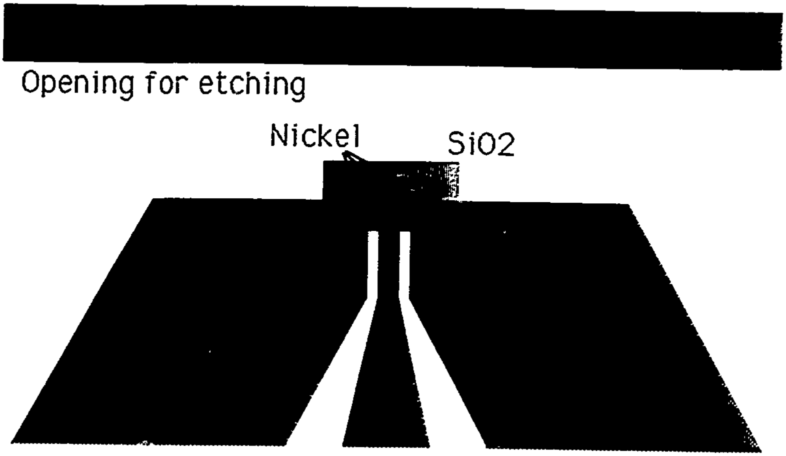

Fig. 8 Close up view of through-line tip mask

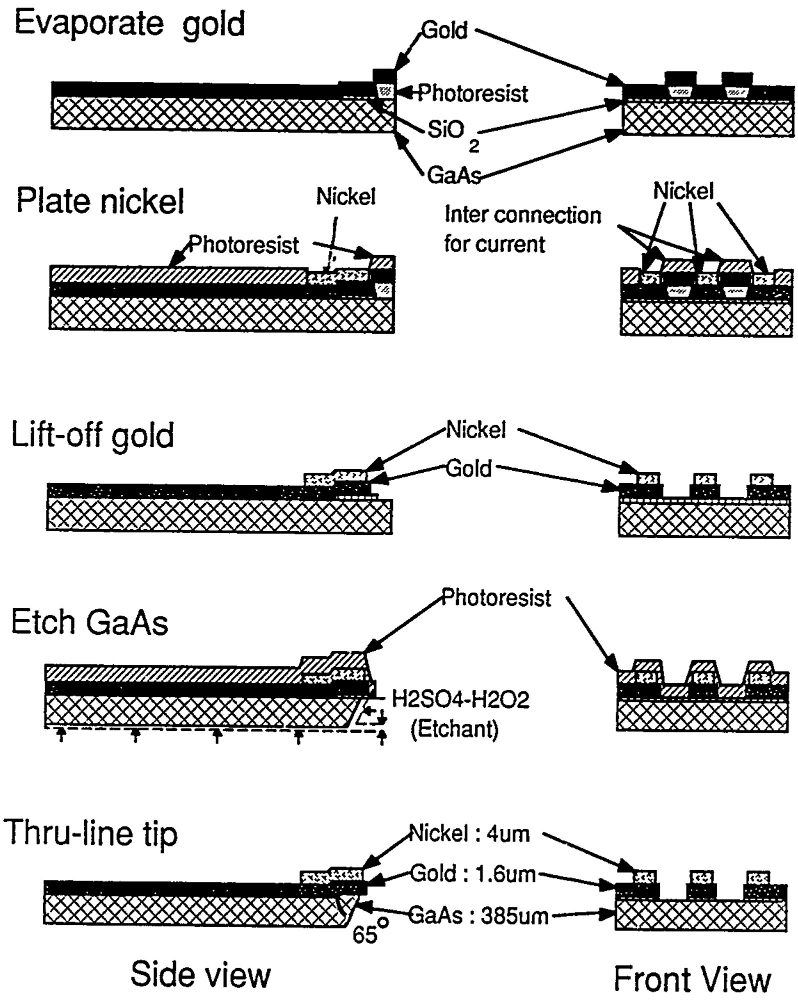

Fig. 9 Tip processing

F. Microwave Characterization

The 50 GHz GaAs through-line probe consists of the following components: 2.4 mm connector, 2.4 mm connector to 22 mil coax transition, 7 cm of 22 mil coax, CPW alumina through-line and GaAs through-line tip. Loss and input match of the GaAs probe were measured using the HP8510C 50 GHz network analyzer. Output match was measured by calibrating the output of a 50 GHz cascade probe and using a 90/60 to 20/13 CPW transition circuit. In addition, a 2.4 mm connector to 22 mill coax, a 22 mil coax to alumina CPW through-line and a CPW GaAs tip to CPW DUT transitions were measured by using the network analyzer time domain and gating options (Table 3).

Table 3

DC-50 GHz GaAs Probe

Input match		-9 dB
2.4 mm connector to 22 mil coax transition		-13 dB
22 mil coax to alumina CPW transition		-16 dB
Output match		-10 dB
Probe loss at freq. =	1 GHz	.5 dB
	5 GHz	1.5 dB
	10 GHz	2.5 dB
	25 GHz	3.6 dB
	40 GHz	10 dB
	50 GHz	16 dB

Next the GaAs through-line probe was connected to a HP8510C network analyzer by two 2 feet flexible cables which had 3 dB loss at 50 GHz. Calibration standards such as CPW open, short, offset short, thru and line with 90/60 and 20/13 dimensions were fabricated on a semi-insulating GaAs substrate (Fig. 10). A load standard was not included in this run, for ease of processing.

In one-port network analyzer measurement, three known standards are needed to define directivity, source match and tracking errors. For two-port calibrations a thru standard is also required. Without a load standard, two main calibration techniques are commonly used: open / short / offset short and thru / reflect / line (TRL - for two-port calibration only). The TRL calibration technique failed because the high losses of the flexible cable and the GaAs probe invalidated the TRL mathematical assumptions in HP8510C network analyzer firmware. Calibration was good below 25 GHz using open / short / offset short standards. The calibration above 25 GHz was very noisy due to the high loss of the probe. Simple network analyzer error analysis shows that with 10 dB through loss the directivity sensitivity is reduced by a factor of 10. The effect of loss on the network analyzer one-port calibration was evaluated by adding a 10 dB attenuator at the output of the HP8510B 26 GHz network analyzer. The measurement data after simple open / short / load calibration was very noisy compared to the no loss condition. With the addition of a 10 dB attenuator, the raw network analyzer data is close to the middle of the Smith chart, in which small errors in calibration standard or measurement can cause major errors. With high through loss, the open/short/ offset short calibration was worse than open / short / load calibration because for offset short standard the offset transmission line must exactly be known.

Contrary to the general belief that calibration can solve all measurement problems in a network analyzer measurement, the actual raw system performance of the network analyzer is critical to good measurement . Also additional loss following the couplers significantly degrades the network analyzer performance and a load standard is a must.

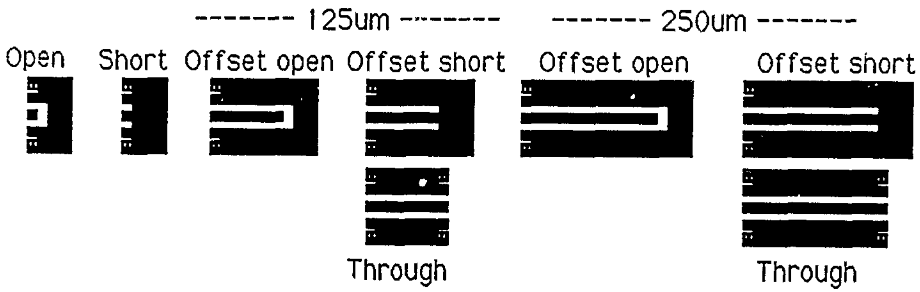

Fig. 10 Calibration standards 20/13 CPW

IV. Future Plan

To date, we have developed an on-wafer GaAs through-line probe, a MMIC S-parameter chip, and a 100 GHz MMIC multiplier. In the design of the GaAs active probe, the S-parameter chip and the MMIC multiplier will be fabricated in the probe tip in order to increase the bandwidth of on-wafer S-parameter measurements to 300 GHz. The GaAs active probe development will consist of three main tasks:

1) Design of the 300 GHz bandwidth GaAs tip using a 3-dimensional field solver.
2) Integration of the S-parameter MMIC on the GaAs tip.
3) Development of 300 GHz CPW standards.